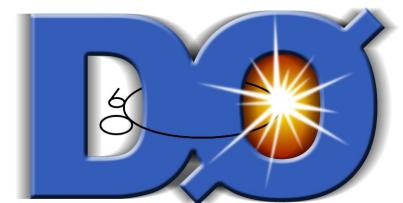


W/Z+Jets and W/Z+HF Production at the Tevatron

Stefano Camarda¹



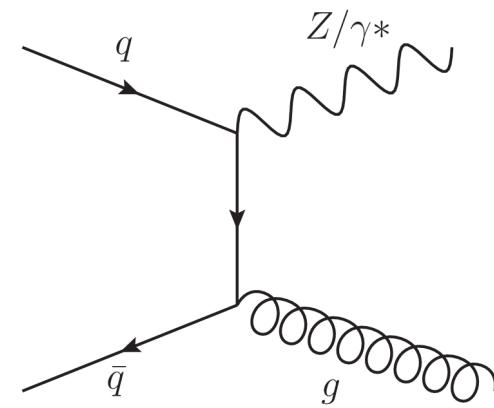
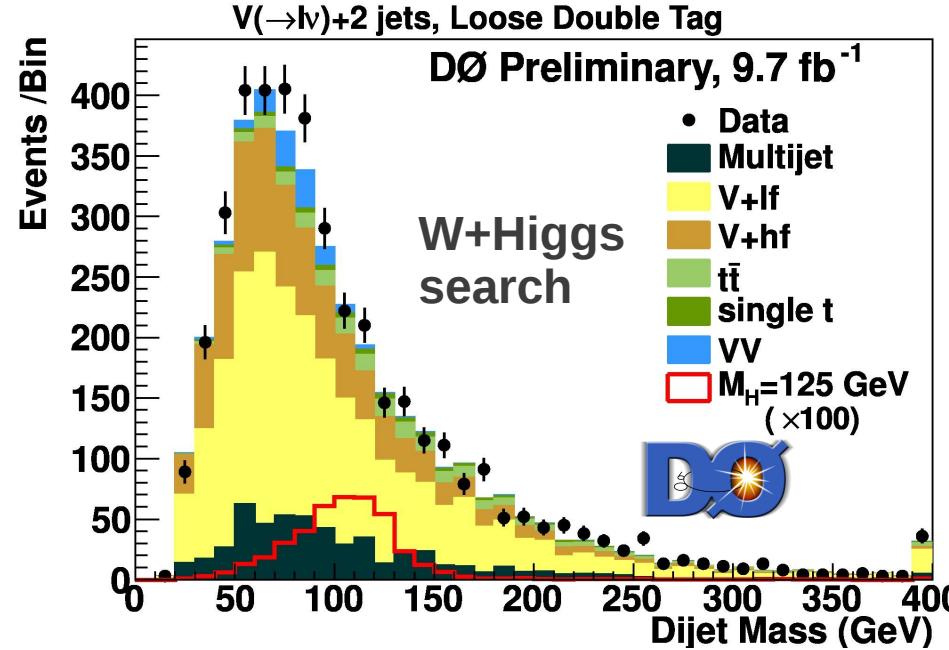
On behalf of the
CDF and DØ Collaborations



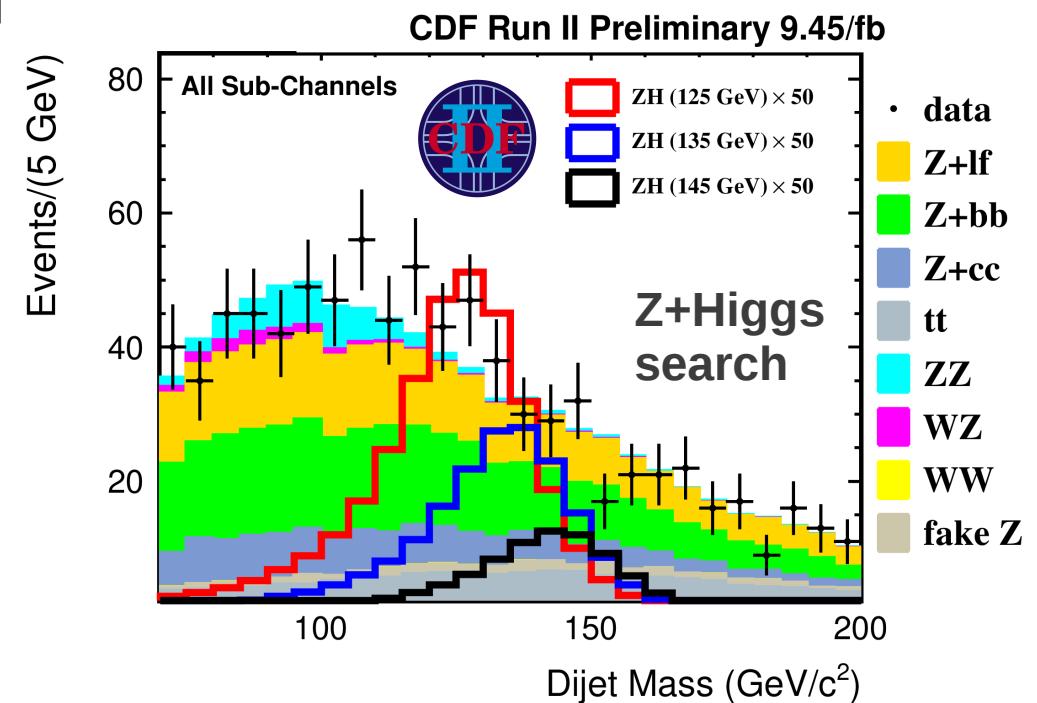
**Moriond QCD
March 9-16, 2013
La Thuille**

¹Formerly IFAE - Barcelona

Motivation

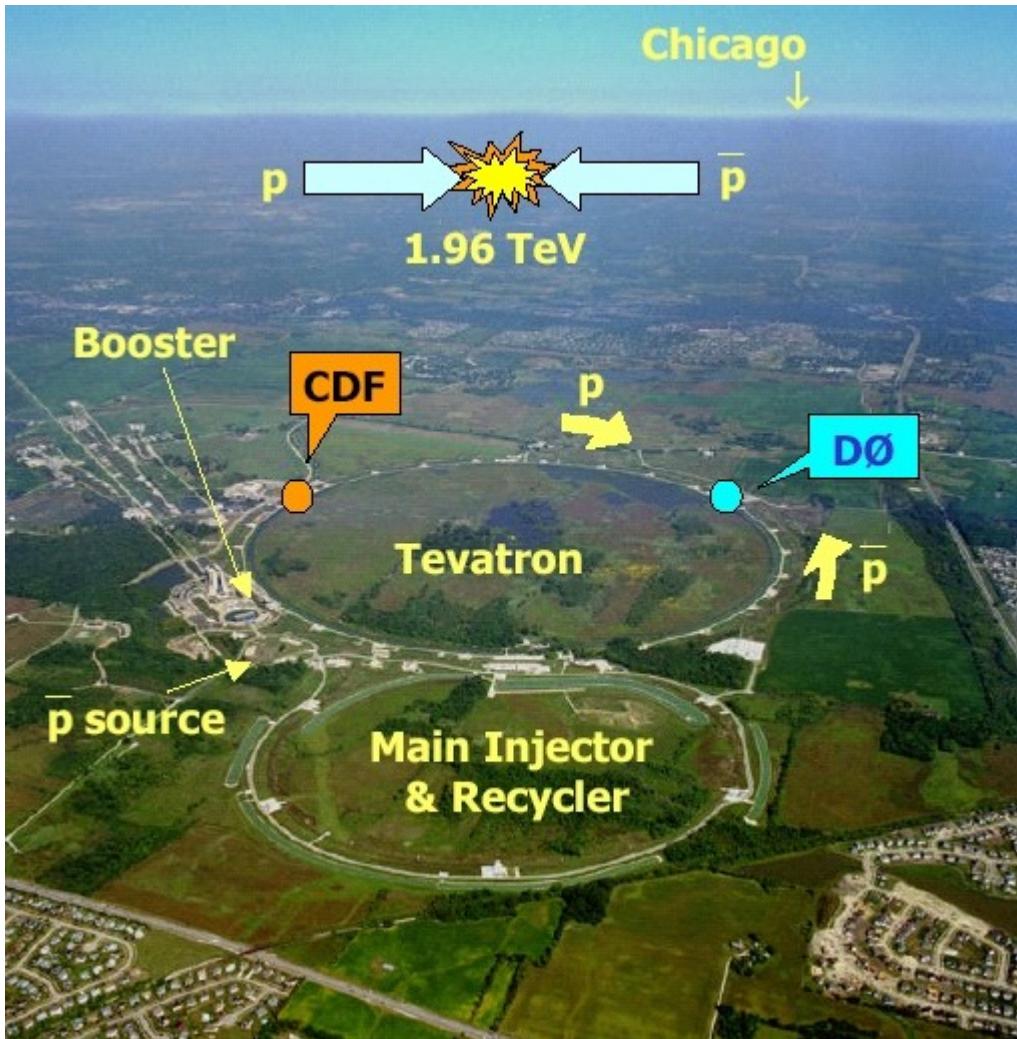


- Test perturbative QCD at high Q^2
- Background for rare SM processes (top, diboson, Higgs) and new physics searches

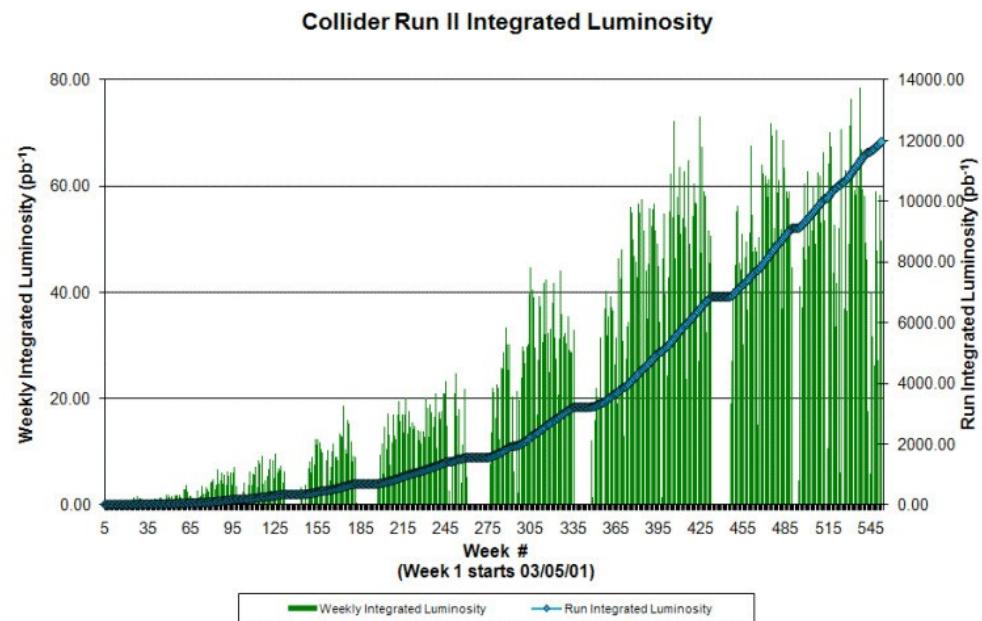


Tevatron Run II

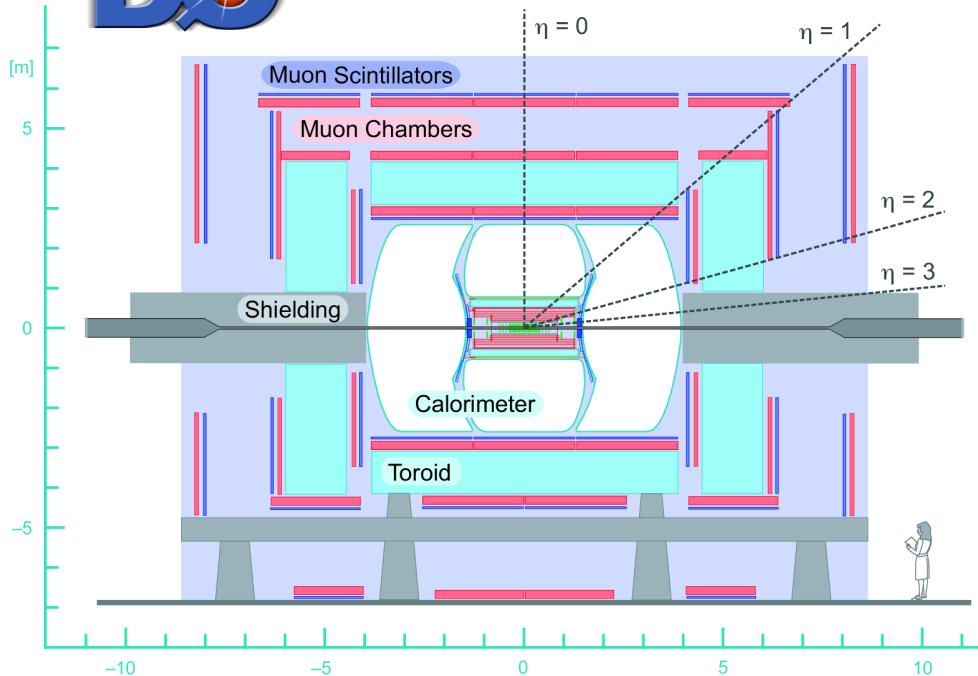
Full Tevatron Run II dataset
12 fb^{-1} delivered – 10 fb^{-1} for analysis



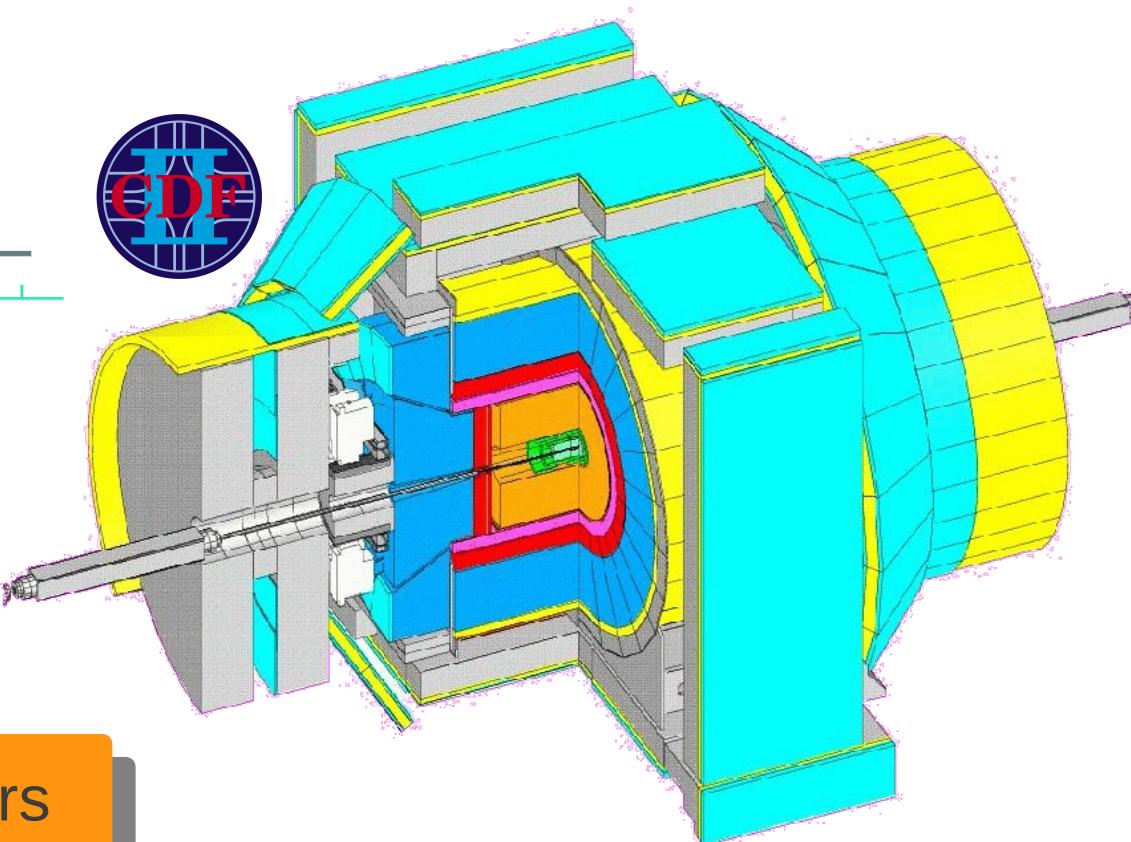
- $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$
- Peak instantaneous luminosity $\sim 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- 10 years of data acquisition, end of operation in September 2011



DØ and CDF detectors



Multi purpose detectors



- Central Tracking systems
- Calorimeters
- Muon detectors

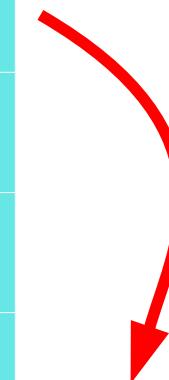
Well known detectors

W/Z + Jets and HF recent results from the Tevatron

Measurements with associated luminosity

W/Z + Jets W/Z + HF

| Final State | Luminosity | Detector |
|--------------------------------------|--------------------------------|---|
| $Z \rightarrow l^+l^- + \text{Jets}$ | 10 fb$^{-1}$ |  |
| $W \rightarrow e\nu + \text{Jets}$ | 4 fb $^{-1}$ |  |
| $Z + b\text{-jets}$ | 9 fb$^{-1}$ |  |
| $Z + b\text{-jets}$ | 10 fb$^{-1}$ |  |
| $W + b\text{-jets}$ | 6 fb $^{-1}$ |  |
| $W + \text{charm}$ | 4 fb $^{-1}$ |  |

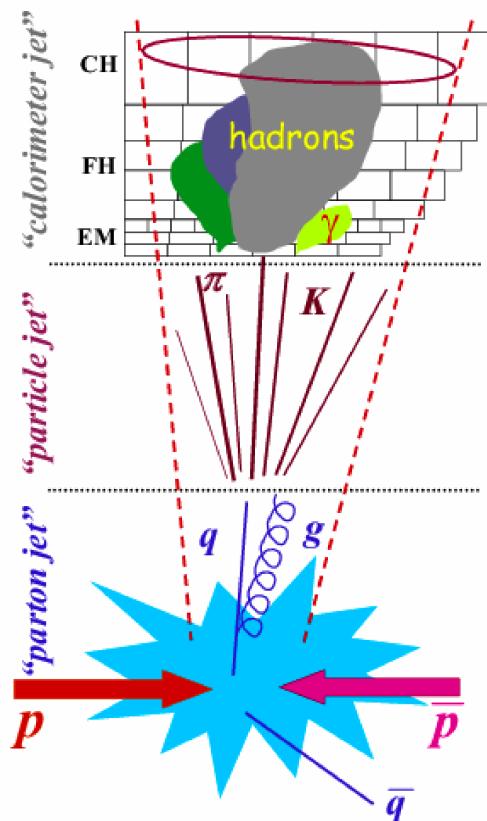


W/Z + Jets measurements

High p_T central electrons or muons provide a clear signature → trigger

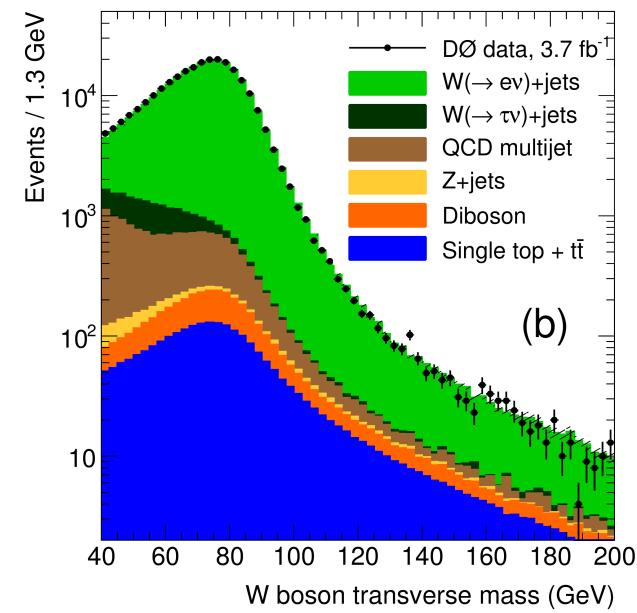
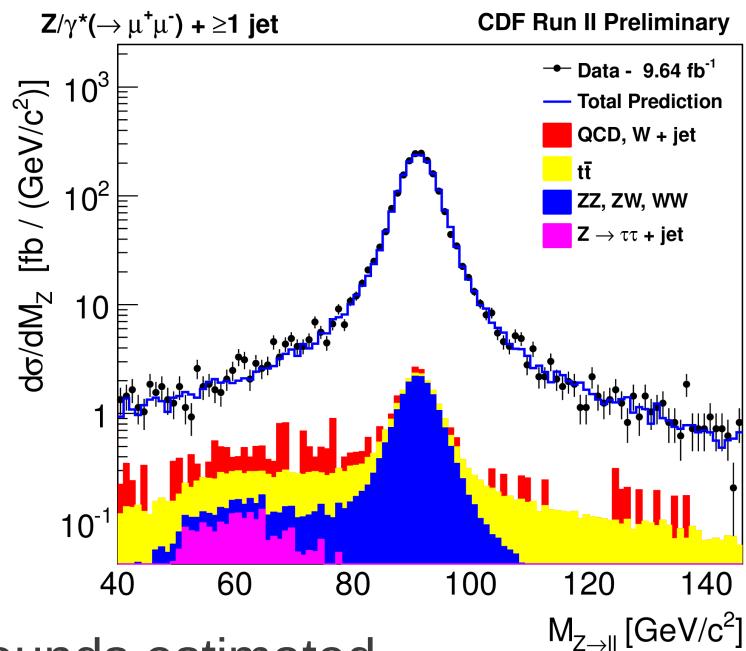
Midpoint jet algorithm

- $R = 0.7$ - CDF Z+jets
- $R = 0.5$ - D0 W+jets

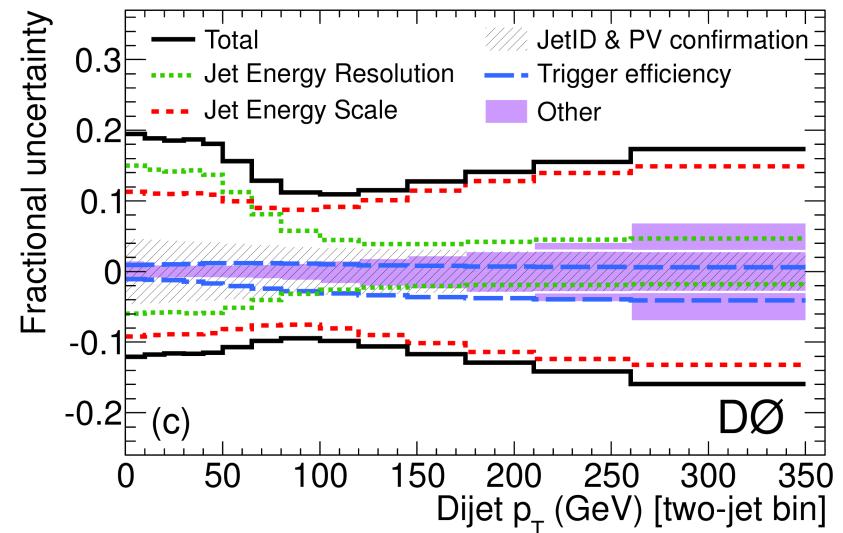
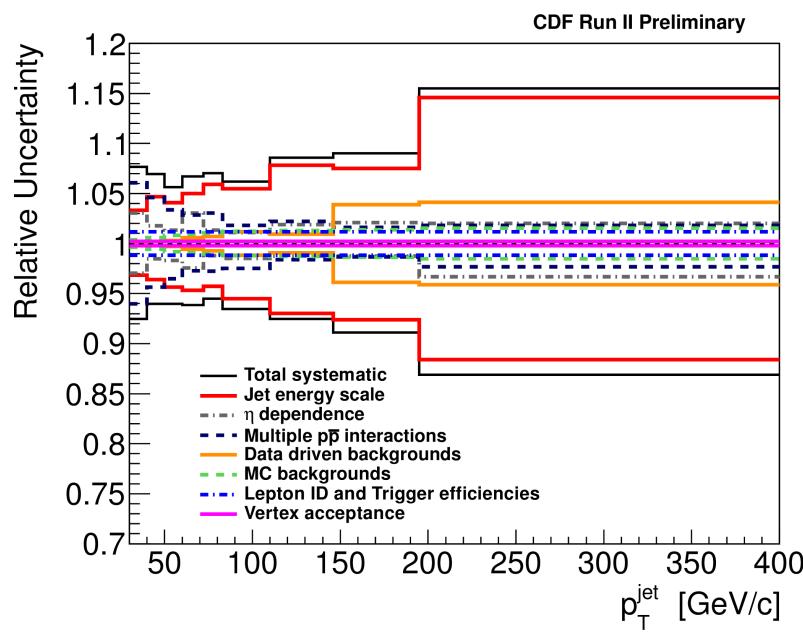


Backgrounds estimated with MC and data-driven techniques

Detector level cross sections unfolded back to particle (hadron) level



W/Z + Jets measurements



Jet Energy Scale is the main systematic uncertainty

Data compared to many theoretical predictions

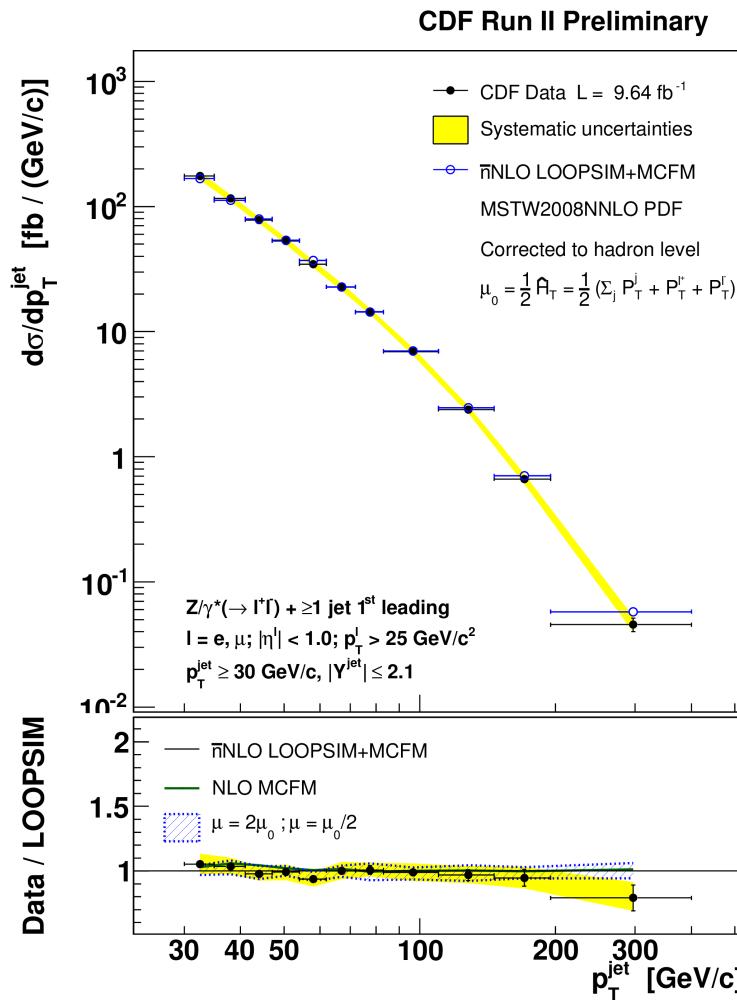
- Largest theory uncertainty: μ_0 scale variation
- PDF uncertainties: 2%-4%

- **MCFM and BLACKHAT+SHERPA**
NLO fixed order perturbative QCD
- **ALPGEN and SHERPA**
Matched LO-ME+PS
- **POWHEG+PYTHIA**
Merged NLO+PS
- **PYTHIA - HERWIG**
LO+PS Monte Carlo
- **HEJ**
Wide angle resummation
- **LOOPSIM+MCFM**
Approximate nNLO
- **NLO QCD x NLO EW**
Factorized NLO QCD and EW

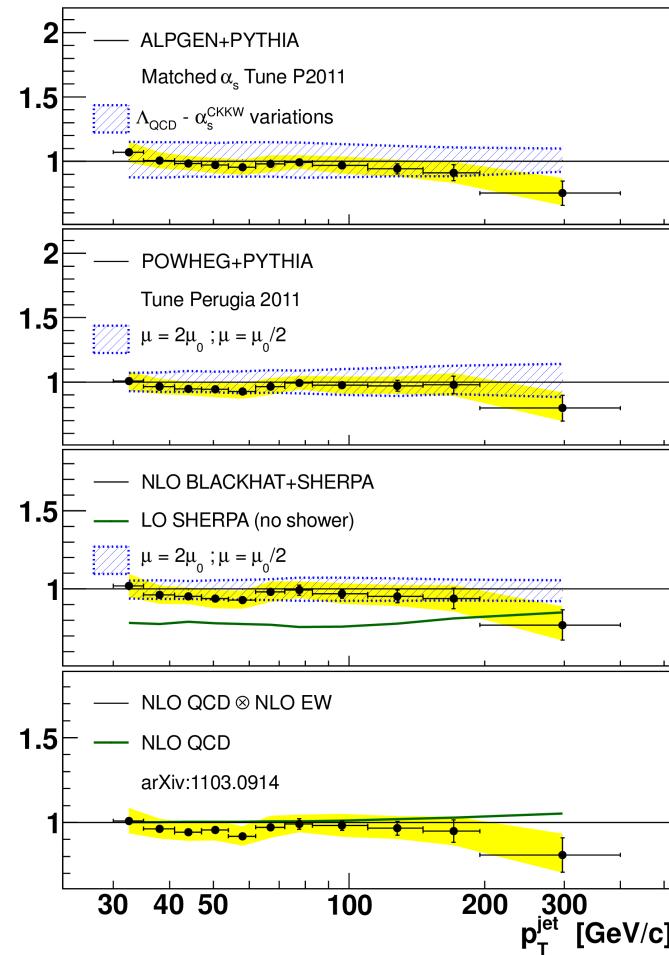
Z/ γ^* + Jets

Extensive study of many differential cross sections
 Jet p_T , $|y|$, H_T , di-jet mass, $\Delta\phi$, ΔR , jet multiplicity

FERMILAB-THESIS-2012-12
 CDF public note 10216



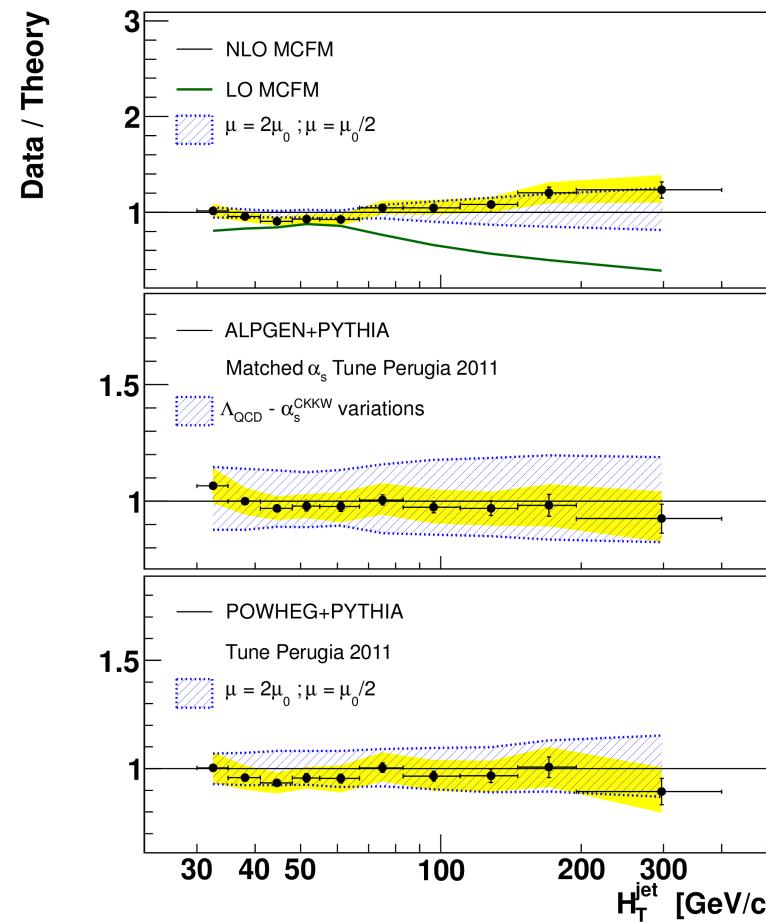
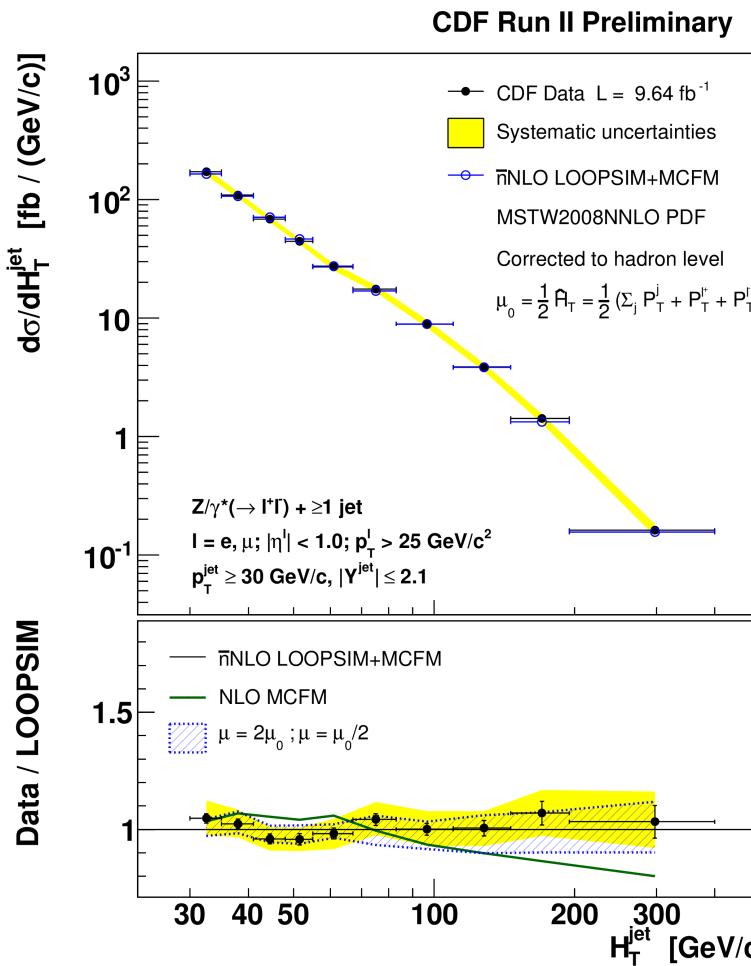
Comparison to several predictions



- LOOPSIM+MCFM only 4%-6% scale uncertainty
- NLO EW correction ~5% at high pt → large virtual Sudakov logarithms

$Z/\gamma^* + \geq 1$ jet H_T^{jet}

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CDF public note 10216

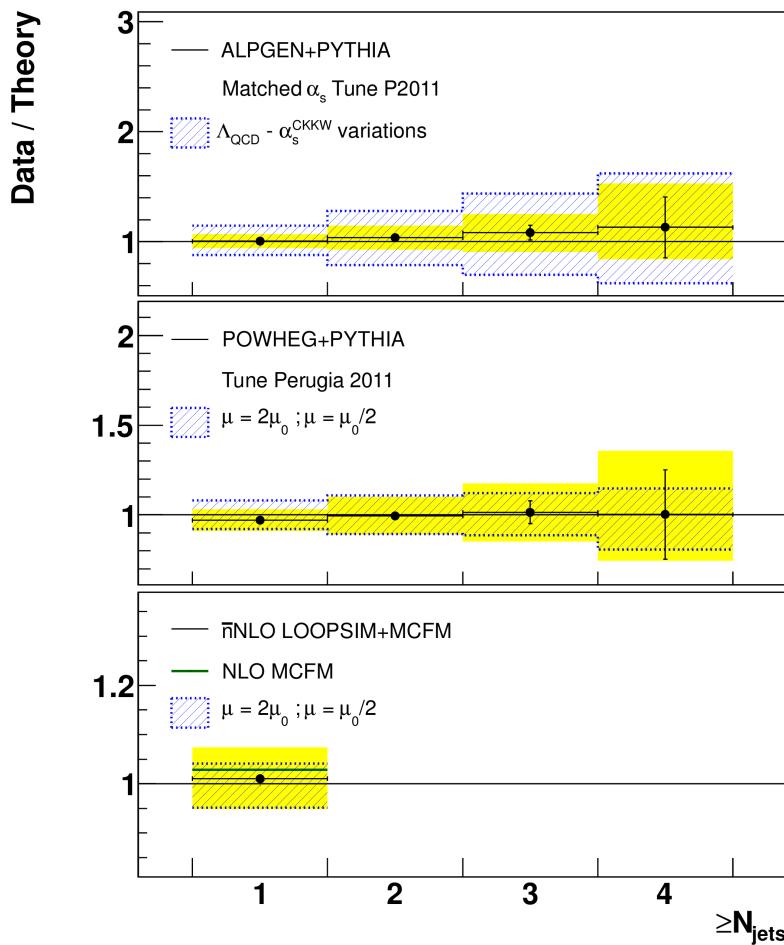
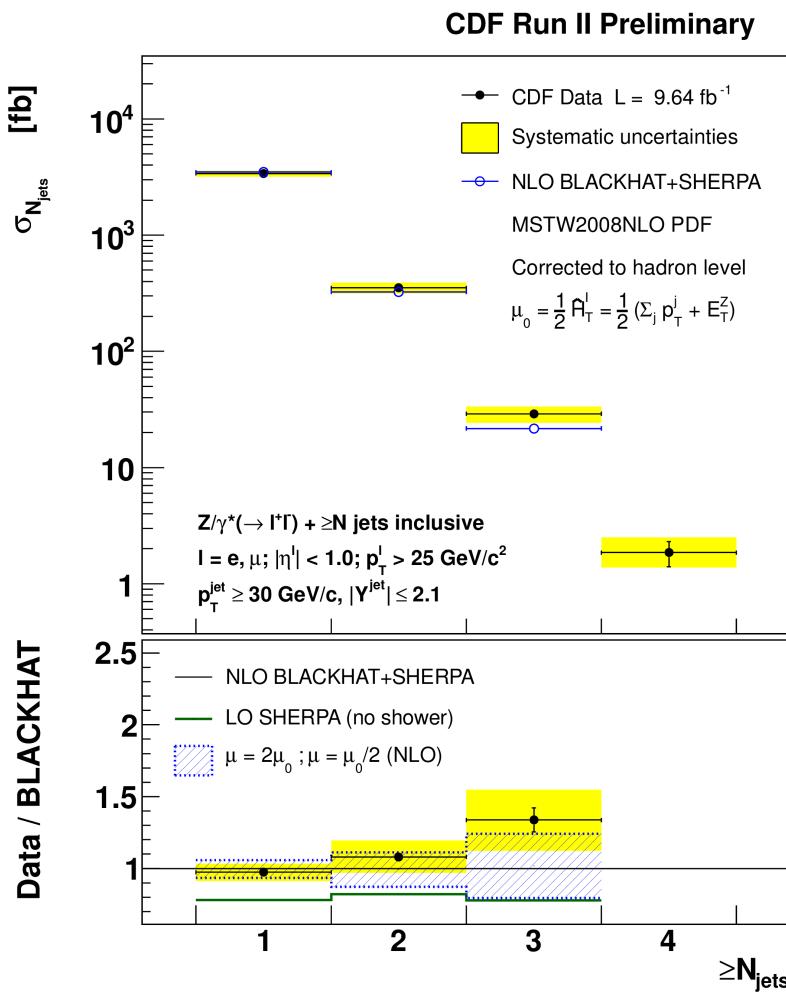


- Large NLO/LO K factor ≥ 2 at high $H_T^{\text{jet}} = \sum p_T^{\text{jet}}$ → Significant beyond NLO corrections
- LO-ME+PS (ALPGEN) and NLO+PS (POWHEG) properly model data with large scale uncertainty
- Good modeling of approximate nNLO LOOPSIM with reduced scale uncertainty



Z/ γ^* + $\geq N$ jets

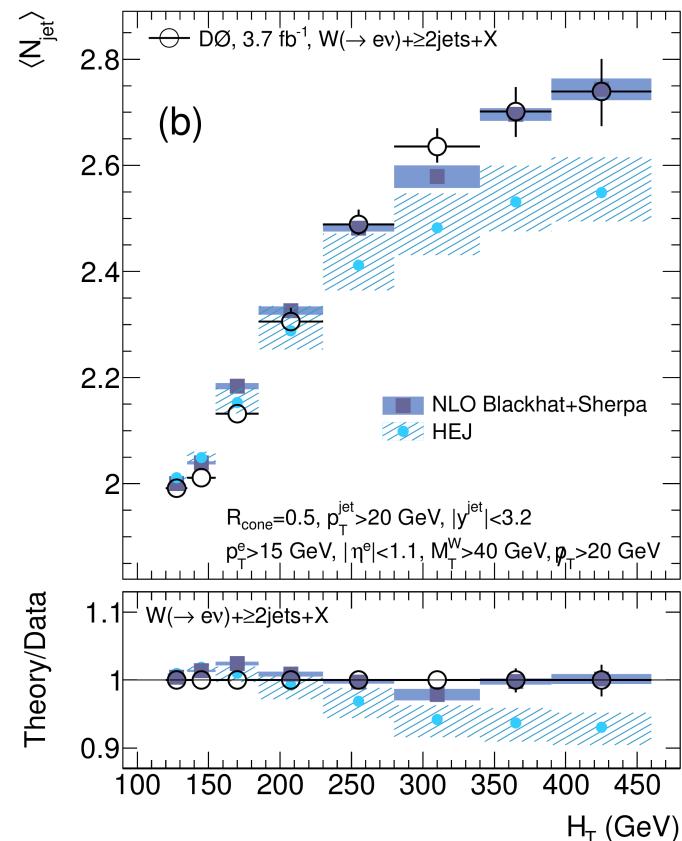
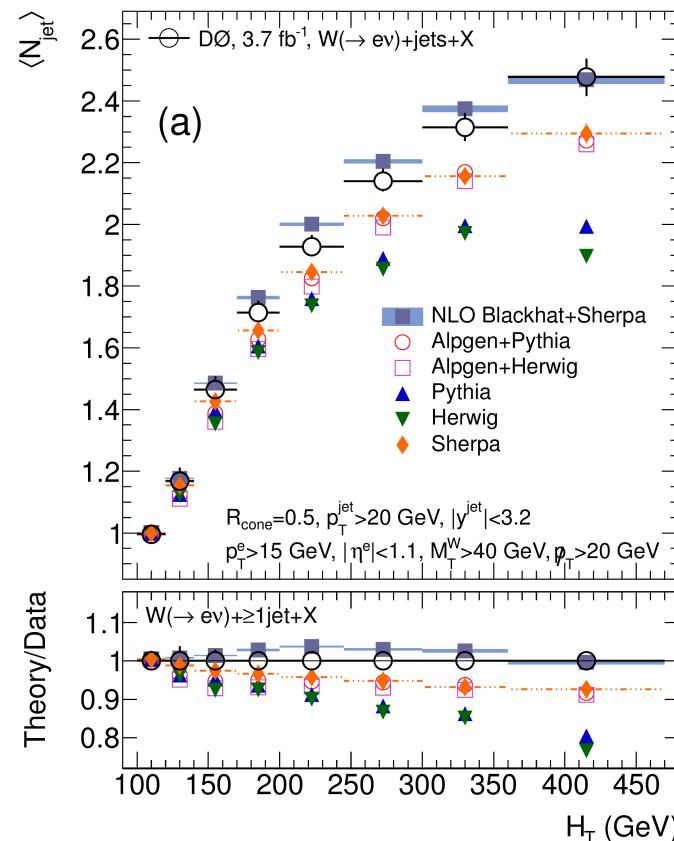
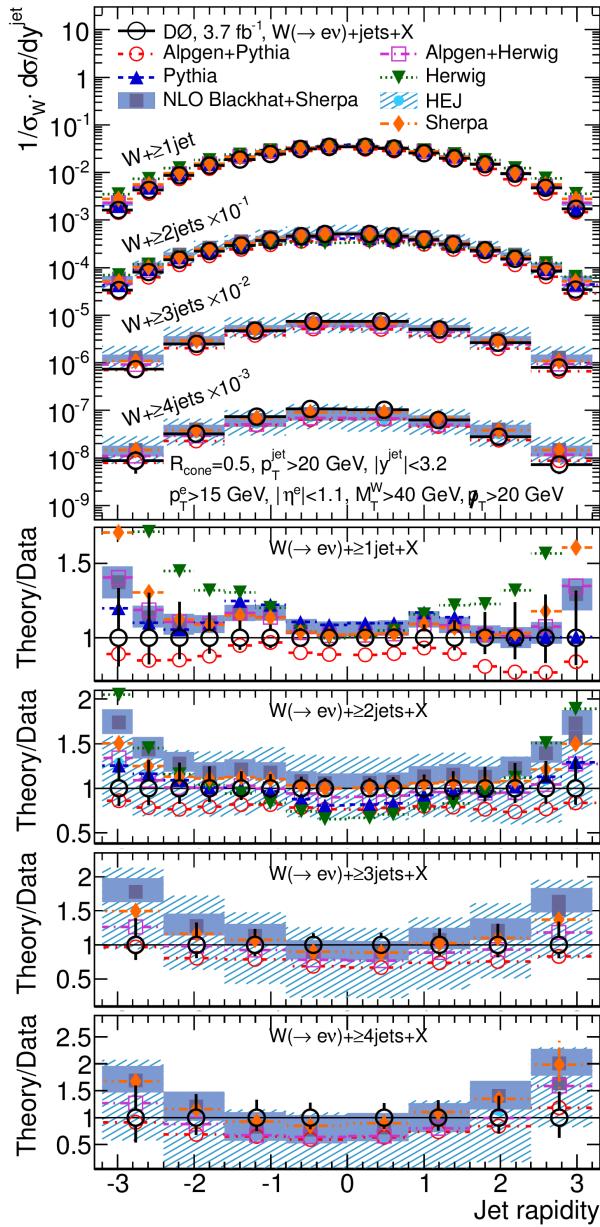
FERMILAB-THESIS-2012-12
CDF public note 10216



- LOOPSIM+MCFM scale variation lower than experimental uncertainty
- NLO pQCD underestimates measurement at high jet multiplicity
 - effect due to the modified “jet reach” of cone algorithms in the presence of QCD radiation



Comprehensive study, measured 40 differential cross sections

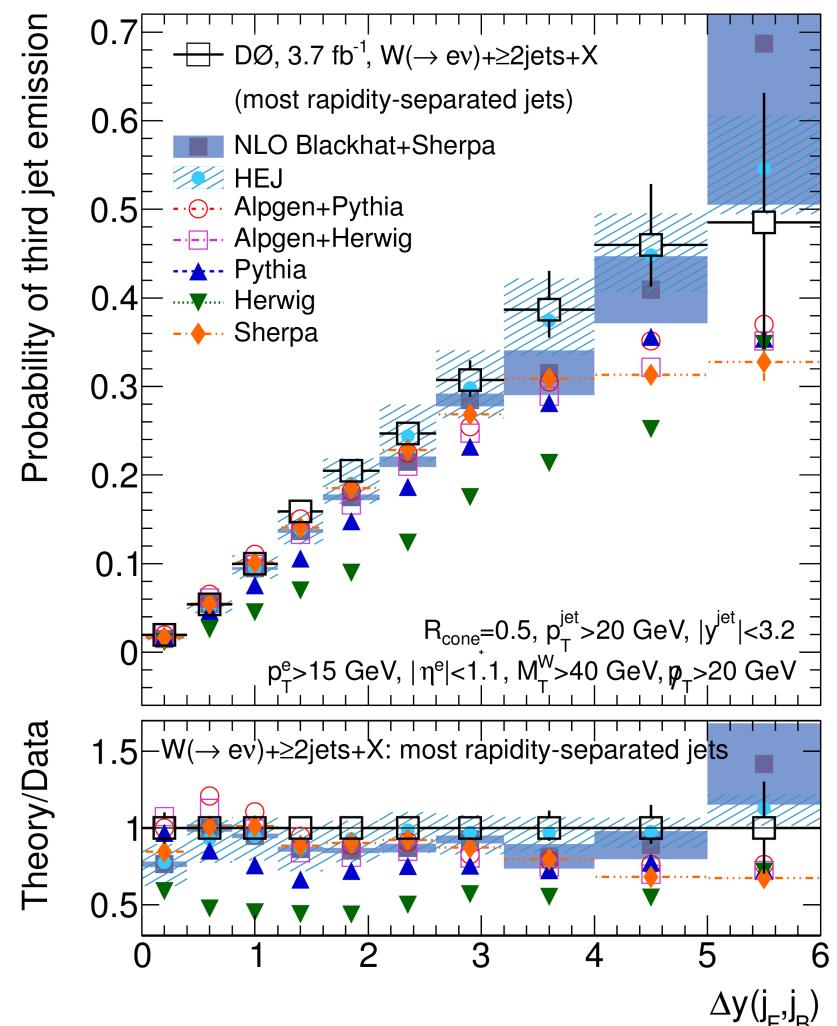
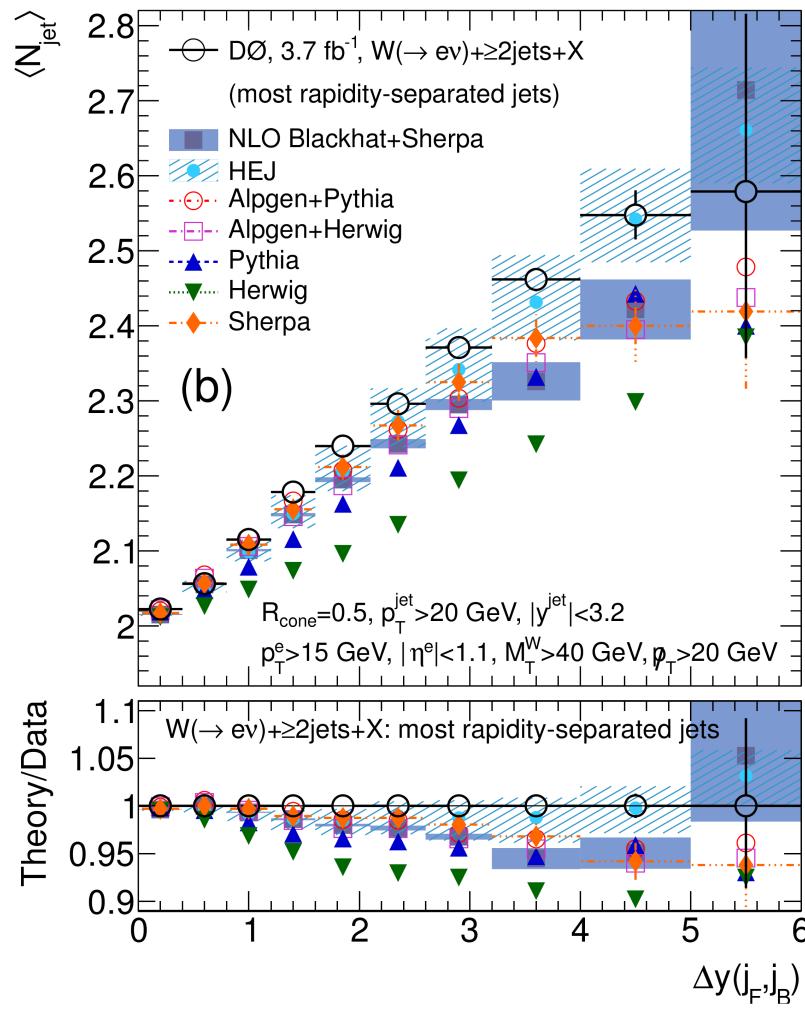


NLO BLACKHAT in good agreement with data

$$\langle N_{\text{jet}} \rangle = n + (d\sigma_{n+1}^{NLO} + d\sigma_{n+2}^{LO}) / d\sigma_n^{NLO}$$



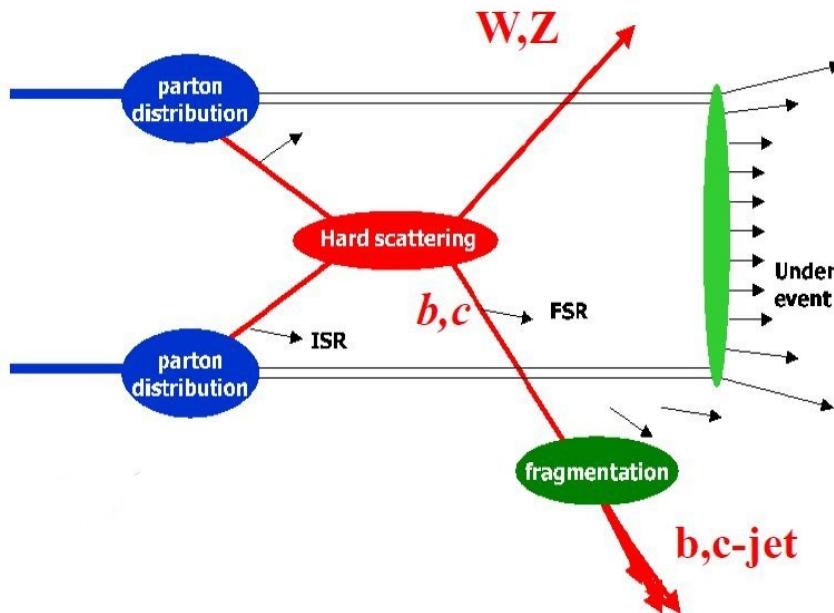
HEJ large-angle resummation provides a good description of data at wide di-jet angle



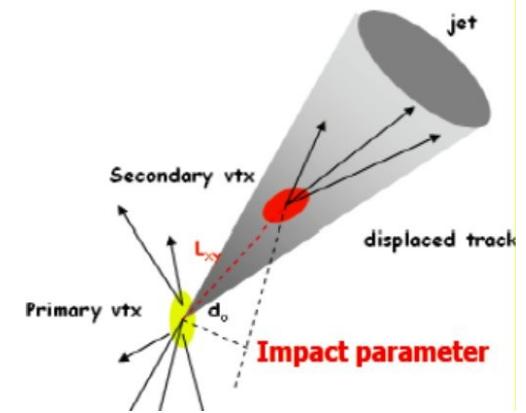
W/Z + HF Jets measurements

Challenging experimental measurements

- b and c identification
- Low statistics



Secondary vertex tag
based on large B lifetime



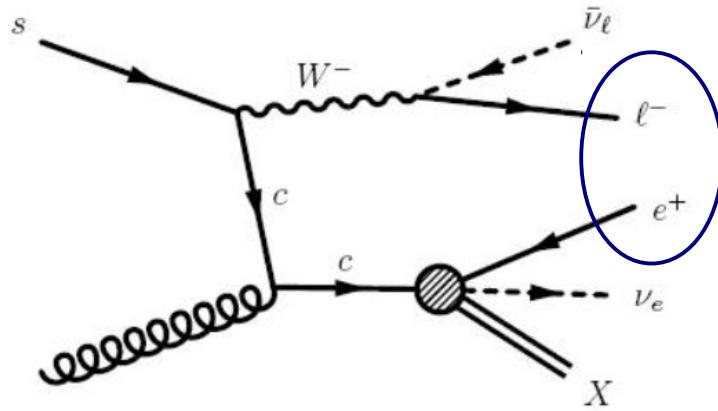
Soft Lepton tag
(20% Branching ratio)

Challenging theory predictions

- Large variation wrt to scale choice
- PDF uncertainties at high momentum fraction x

$W + \text{charm}$

Probe s -content of proton at high x, Q^2



Exploit opposite charge correlation between W and charm leptons

Charm-jet identified with a soft lepton tagging (SLT) algorithm

$$\sigma_{W+c} \times Br(W \rightarrow l \nu)$$

$$13.6 \pm 2.2 (\text{stat})^{+2.3}_{-1.9} (\text{syst}) \pm 1.1 (\text{lumi}) \text{ pb}$$

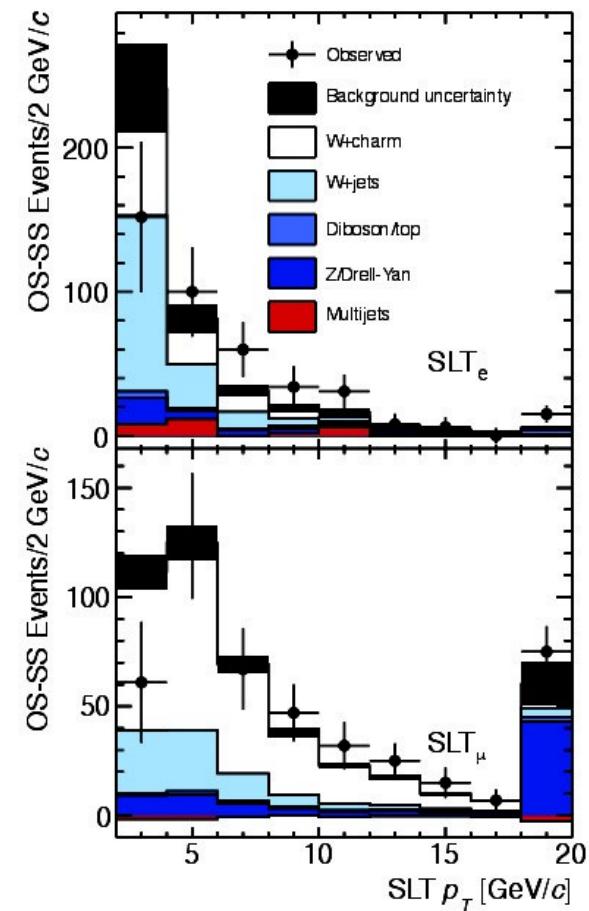
MCFM NLO prediction

$$11.4 \pm 1.3 \text{ pb}$$

Phys.Rev.Lett. 110 (2013) 071801



$L = 4 \text{ fb}^{-1}$

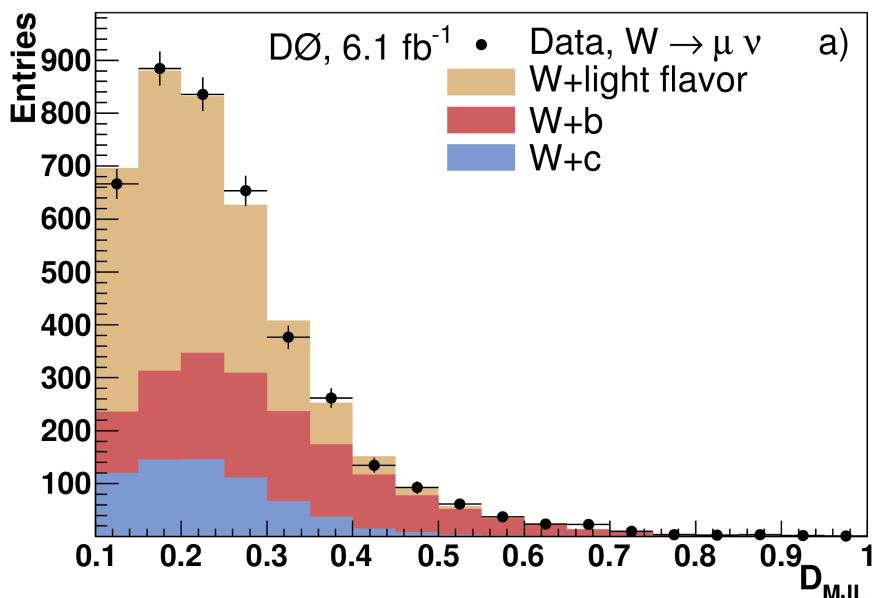


$W + b\text{-jet}$

Excess of $W+b$ production over NLO observed previously by CDF (1.9 fb^{-1})

$$\begin{aligned}\sigma_{W+b} \times Br(W \rightarrow l\nu) \\ = 2.74 \pm 0.27 \pm 0.42 \text{ pb}\end{aligned}$$

$$\text{NLO } pQCD = 1.22 \pm 0.14 \text{ pb}$$

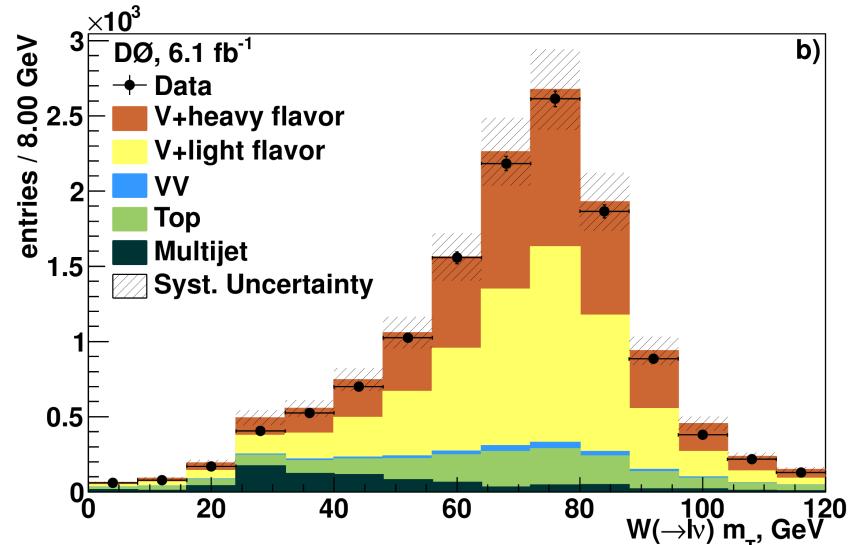


$$MCFM \text{ NLO} = 1.34^{+0.41}_{-0.34} \text{ pb}$$

$$SHERPA = 1.21 \text{ pb}$$

$$MADGRAPH = 1.54 \text{ pb}$$

Phys.Lett. B718 (2013) 1314-1320

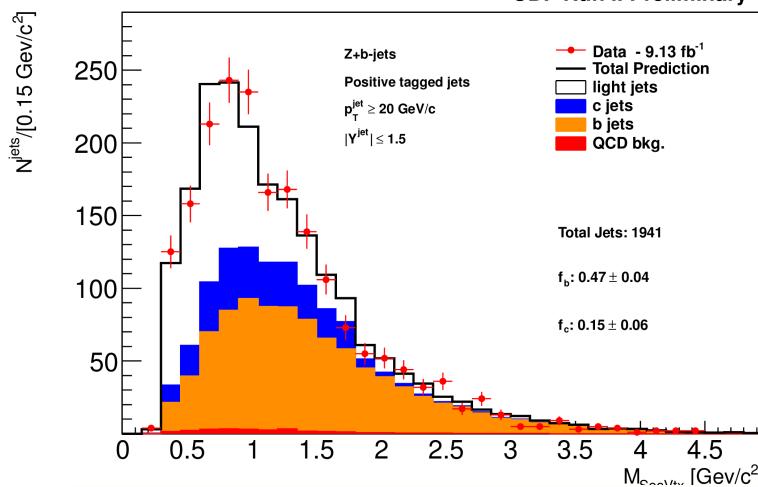


b-jet fraction extracted with MVA b-tagging and secondary vertex mass

$$\begin{aligned}\sigma_{W+b} \times Br(W \rightarrow l\nu) \\ = 1.05 \pm 0.03 (\text{stat}) \pm 0.12 (\text{syst}) \text{ pb}\end{aligned}$$

New precise measurement in agreement with theory predictions

Z + b-jet



$$\frac{\sigma_{Z\text{-}bjet}}{\sigma_Z} = 0.261 \pm 0.023^{\text{stat}} \pm 0.029^{\text{syst}} \%$$

$$\frac{\sigma_{Z\text{-}bjet}}{\sigma_{Z\text{-}jet}} = 2.08 \pm 0.18^{\text{stat}} \pm 0.27^{\text{syst}} \%$$

Differential measurement as a function of b-jet p_T and y

→ b-jet composition extracted with a fit to the secondary vertex mass

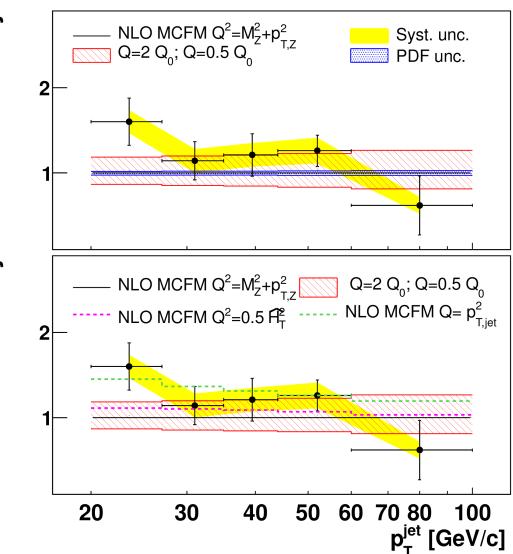
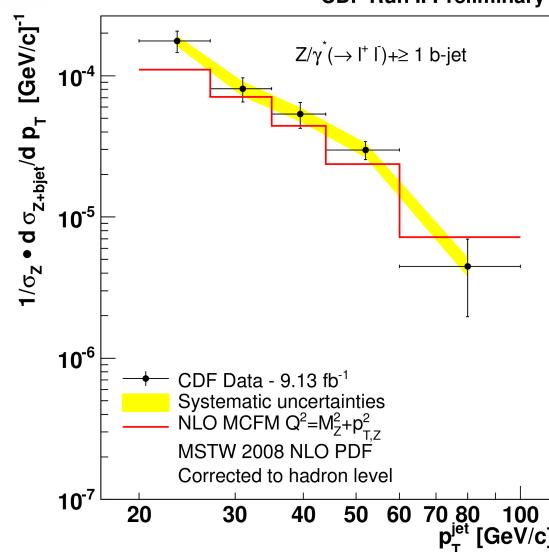
CDF public note 10594



Measured cross sections in good agreement with MCFM NLO

MCFM NLO prediction

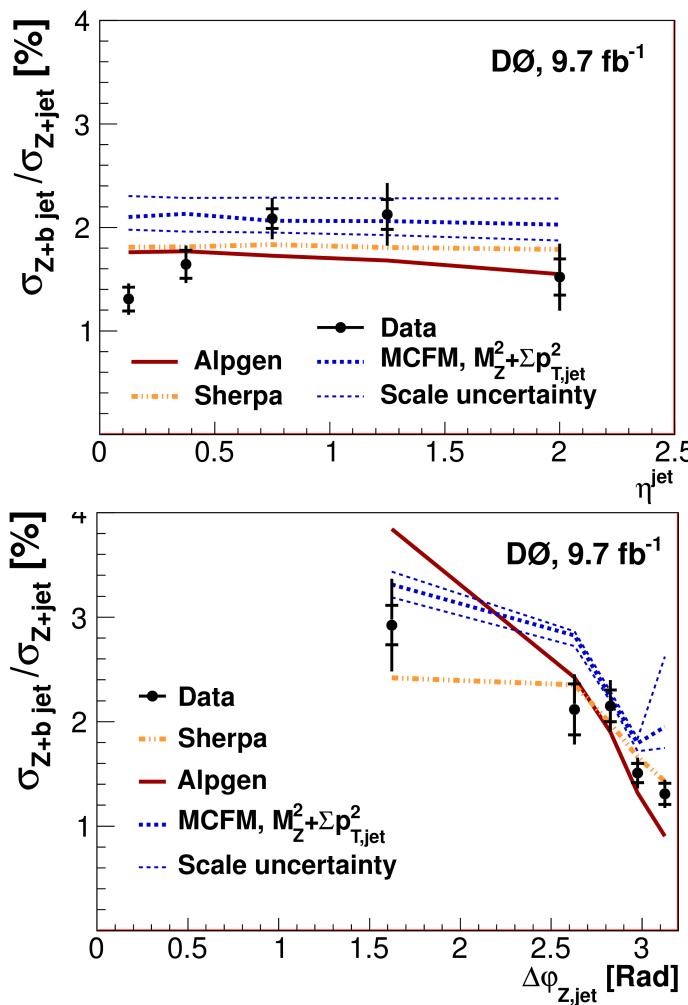
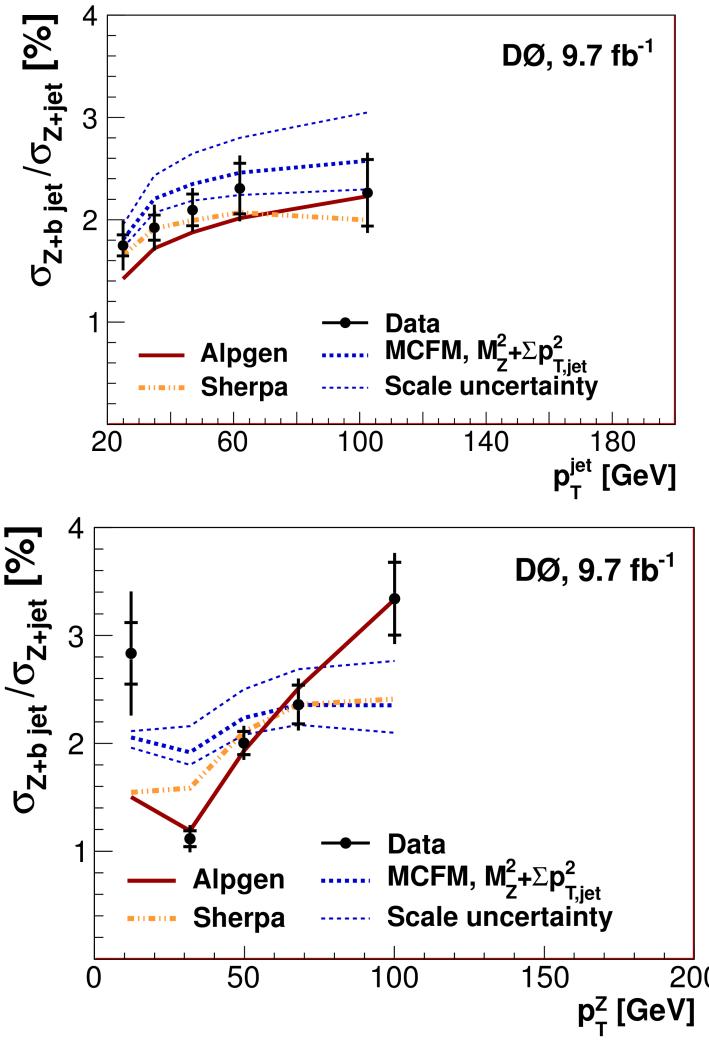
| | $Q^2 = m_Z^2 + p_{T,Z}^2$ | $Q^2 = \langle p_{T,jet}^2 \rangle$ |
|--|---------------------------|-------------------------------------|
| $\frac{\sigma_{Z\text{-}bjet}}{\sigma_Z}$ | 0.23 % | 0.29 % |
| $\frac{\sigma_{Z\text{-}bjet}}{\sigma_{Z\text{-}jet}}$ | 1.8 % | 2.2 % |



$Z + b$ -jet

Measurement of differential cross sections as a function of b -jet p_T and η , Z p_T , and $\Delta\phi(Z, b\text{-jet})$

arXiv:1301.2233



Data compared to

- MCFM NLO
- Algen+Pythia
- Sherpa

Reasonable agreement
with NLO pQCD and
ME-LO+PS

Conclusions



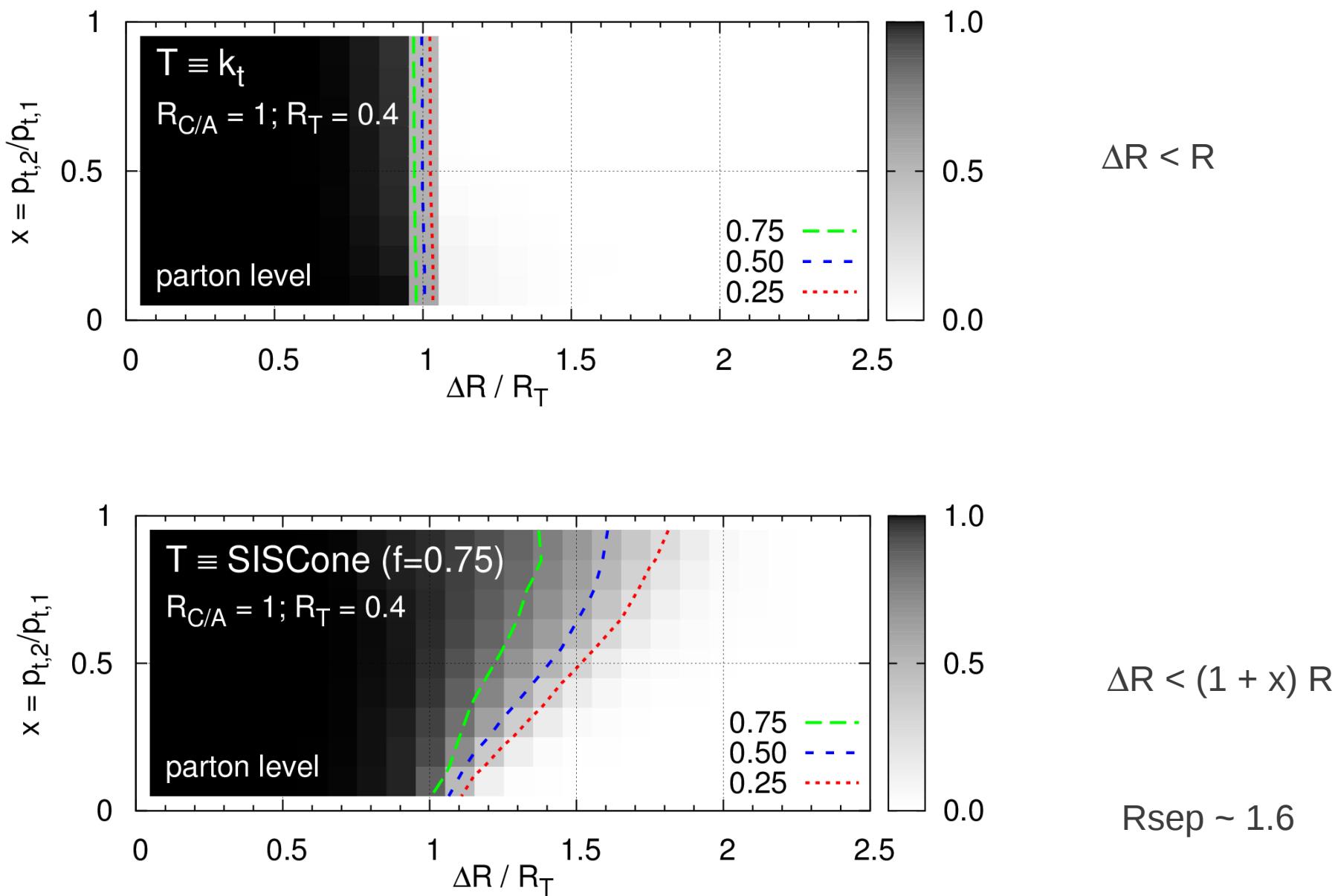
- Tevatron legacy measurements of W/Z + Jets and W/Z + HF
- General good agreement with NLO predictions
- Important test of different theoretical predictions

More details at:

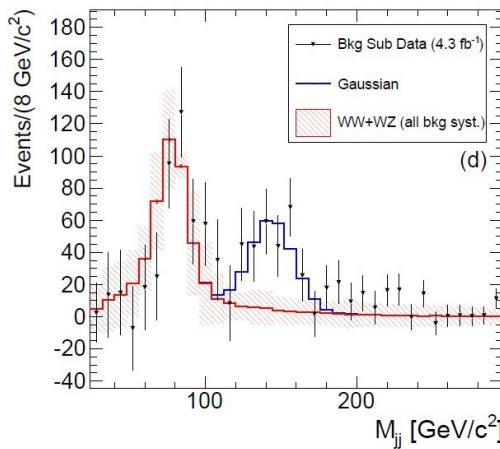
- <http://www-cdf.fnal.gov/physics/new/qcd/QCD.html>
- <http://www-d0.fnal.gov/Run2Physics/qcd/>

BACKUP

$Z + \geq N$ jets - BLACKHAT



$W + jj$ invariant mass



April 2011 - CDF finds an excess not confirmed by other experiments
March 2013 - Analyzed full dataset, several checks performed

Identified two important pitfalls

- Modeling of jet pt in the simulation
- QCD background in $W \rightarrow e\nu$ channel

W+jj di-jet invariant mass in good agreement with SM background expectation

